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Discovering the Cubango-Okavango River Basin

A geomorphological description of the Angolan rivers and its fish assemblages and the ecological implications of future human development

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Abstract

The years fly by but the African continet and its enourmos richness remains an undiscovered treasure. The Angolan province Cuando-Cubango includes one of the biggest watersheds of the African continent, the Cubango-Okavango river basin. One of the rivers where most parts remains untouched and in a pristine form. Ongoing water resources planning intends to regulate large parts of the basin and to intensify human uses. In order to better understand and to analize ecological responses of the Angolan part of this river basin, three main steps were conducted: The first one was to develop and to validate a geomorphological zonation in order to understand the evolution and the main characteristics of river planforms. In second place, the different fish species that inhabit the main water courses where taken into account and a fish zonation was designed for the entire watershed in order to establish biological responses based on the species's needs and their connectivity dependence. The projected dams' construction for the different rivers was analized and their impacts on the species movements and habitat exploitation were desmasked in order to understand the ecological implications of this constructions for the watershed enviroment.

Key-words: Cubango-Okavango; geomorphologic; fish; zonation; connectivity

Resumo

Os anos passam, mas o continete Africano e a sua enorme riqueza continua a ser um tesouro desconhecido. A província angolana do Cuando-Cubango inclui uma das maiores bacias hidrográficas do continente Africano, a bacia do rio Cubango-Okavango, um dos rios onde a maioria das regiões permanece de forma inviolada. O planeamento atual dos recursos hídricos da região pretende regularizar grandes partes da bacia, o que consequentemente levará à intensificação da presença humana. Foram definidas três grandes etapas a fim de melhor compreender e analisar as respostas ecológicas da parte angolana da bacia. A primeira foi desenvolver e validar uma zonação geomorfológica, a fim de compreender a evolução e as principais características dos diferentes rios. Em segundo lugar, foram analisadas as diferentes espécies de peixes que habitam nos principais cursos de água. Projetou-se uma zonação piscícola para toda a bacia hidrográfica a fim de obter respostas biológicas com base nas necessidades das espécies e da sua dependência de conectividade. A construção das barragens projetadas para os rios foi analisadas sendo os seus impactos sobre os movimentos das espécies e os seus respetivos habitats explicitados a fim de compreender as implicações ecológicas destas construções para o ambiente da bacia hidrográfica.

Palavras chave: Cubango-Okavango; geomorfológica; peixe; zonação; conectividade

Resumo alargado

A riqueza que o continete africano apresenta é conhecida mundialmente. Esta riqueza indiscritível verifica-se claramente quando falamos da província angolana Cuando-Cubango localizada no Sul do país na fronteira com a Namibia. Nesta província encontra-se a maior parte da bacia hirdográfica do Cubango-Okavango que se estende ainda pela Namibia e pelo Botswana. Sendo uma das maiores bacias do continente esta está dotada de uma enorme quantidade de linhas de água que desaguam no maior Delta interior do mundo. A grande densidade e dimensão das linhas de água presentes na província do Cuando-Cubango faz com que estas tenham uma enorme importância social, económica e ecológica na região. O grande desenvolvimento que se tem sentido em Angola no últimos anos faz com que o enorme e cativante potencial desta região se torne cada vez mais aliciante do ponto de vista do empreendedorismo. Este enorme potencial aumenta a necessidade de aprofundamento do conhecimento desta provincia e da riqueza que a preenche e levou ao desenvolvimento deste estudo. Desenvolveu-se uma análise geomorfológica e ecológica aos rios do lado angolano da bacia do Cubango-Okavango. Foram definidas três grandes etapas: A primeira foi desenvolver e validar uma zonação geomorfológica, de modo a compreender a evolução e as principais características dos mais importante rios da bacia. Em segundo lugar, procurou-se analisar as diferentes espécies de peixes que habitam os principais cursos de água e criar uma zonação única em que se relacionaram as diferentes distribuições com a zonação geomorfológica criada anteriormente. Como métodos auxiliares foram usados algoritmos estatisticos. Por fim, foi feita uma concretização dos impactos das construções de barragens previstas para os próximos anos nos diferentes rios com base nas necessidades das espécies e da sua dependência da conectividade entre os vários cursos de água. Geraram-se cinco zonas geomorfológicamente distintas e muito claras ao longo da região analisada sendo que a validação se fez no campo com base em variáveis estruturantes dos diferentes canais. Com grande influência da zonagem geomorfológica definiram-se zonas de distribuição de várias espécies documentadas para os diferentes rios sendo que se geraram cinco zonas diferentes. Por analisaram as construções das barragens projetadas para os diferentes rios e os seus impactos nos habitats das diferentes espécies foram revelados de modo a compreender as implicações ecológicas deste construções para o ambiente da bacia hidrográfica. Sendo que estas barragens representam o desenvolvimento da região e o início da pressão humana sobre alguns ecosistemas, o estudo evidencia a perda de conectividade e os impactos negativos a que os habitats e consequentemente as espécies ficam sujeitas.

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‘Continuous effort,
not strength or intelligence,
is the key to unlock our potential!’
(Winston Churchill)

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Introduction

Watersheds are a natural source of life, ecological richness and diversity, whose landscape is shaped by the power of the rivers, streams and brooks that, guided by gravity change its topography, climate, and the distribution of plant and animal species (Moulton & Souza, 2006). Petts and Amoros (1996) defined rivers as a ‘popular source of fascination because of their changing moods from headwater stream to large lowland rivers’. Their functions are crucial in stabilizing and maintaining the livelihood of the people who inhabit them, and this livelihood of communities living around the basin is directly or indirectly associated with it. As time passes and the human occupation of the basins develops, the uses for tourism, agricultural and industrial purposes increase their economic importance (Mbaiwa, 2004) together with the level of disturbance and the consequent loss of species richness and ecosystem integrity (Liermann et al., 2012).

Schumm (1981) resumes the geomorphologic variation along the river basin in three major zones: ‘The headwater zone where water, sediment, particulate organic matter and solutes pass from hill slopes to stream channels. The transfer zone through which materials are transported and at last the storage zone where materials are deposited, stored and many retained for thousands of years’. This year-long variation originates the structural characteristics of the riparian system. The dynamic characteristics of riparian landscapes lead to their shifting mosaics and spatial heterogeneity (Malard et al., 1999). This dynamic riparian diversification varies along the year and has a direct impact on the landscape mixture (Ward & Tockner, 2001; Amoros & Bornette, 2002).

The fish communities (Jackson et al., 2001) are dependent of these geomorphic characteristics and the habitats that they compose (Willis et al., 2004), and the minimum modification, e.g. reduction of connectivity of the riparian system, can have severe consequences (Lamouroux et al., 2006) and lead to atypical disturbances. Dudgeon et al. (2006); Darwall et al. (2008) and Strayer & Dudgeon (2010) all emphasize the importance of freshwater diversity and its different communities. Dudgeon et al. (2006) also deduce that one of the main reasons that can lead to biodiversity reduction is the eradication of some species, and species homogenization amongst systems, due to the habitat alteration.

In the last centuries dam construction has dramaticaly increased (Hall, 2011) and has been one of the major threats for the riverine system and its bioiversity. It is also one of the major reasons for its loss of connectivity (Nilsson, 2000; Liermann 2007, 2012; Branco et al., 2011) and its consequences. However this increase has not yet reached the African continent in full strenght and the free-flowing rivers are still abundant (Liermann et al., 2012), therefore enabling us to test river functioning concepts and to prevent degradation due to unsustainable human development.

The Cubango-Okavango river basin has very few naturally obstructed rivers and posesses a high freshwater biodiversity (Darwall et al., 2008), as stated by the various OKACOM reports (http://epsmo.iwlearn.org/publications/envana/biophysical-reports). However, and according to Lucas & Baras (2001), 'these barriers are short-lived on a biological timescale and they promote habitat heterogeneity rather than homogeneity'.

Larinier (2000) and Lucas & Baras (2001) emphasize the importance of the annual fish migrations to complete life-cycles, and its entire dependence of an undisturbed and free-flowing river site. For Larinier (2000) when 'migrations and other fish movements are stopped or delayed, the quality, quantity and accessibility of their habitat, which plays an important role in population sustainability, can be affected'. Apart from the importance of the consequences previously mentioned and according to IUCN, the South-East of the African continent is still a ritch and unobstructed region, containing high numbers of different species. There are around 41 species considered potamodromous in the Cubango-Okavango basin, representing almost half of the species present, notably from *Barbus* and *Synodontis* genera. These species take on annual migrations to spawn. Therefore, insuring water connectivity during reproduction is a crucial aspect of ecological conservation in the basin. Present water resources planning and development proposes a considerable number of dam structures to be built in the nearest future.

The present study analyses, in a first step, the geomorphologic traits present in the Cubango-Okavango river basin and its relationships with the fish communities and its specific richness. It also predicts the impact on connectivity losses due to the projected dam construction during the next twenty years, helping to select the best combination of dams least problematic to injur natural fish richness and potamodromous life cycles.

Methods

Study area

The Cubango-Okavango Basin (Figure 1) heads are located in the highlands of Central Angola, and present two main watersheds, on northwest part the Cubango River and on northeast the Cuito River. 55% of all water that flows through the basin has its origin on the northwest part and the other 45% come from the northeast part (Mendelsohn & el Obeid, 2004). Both watersheds flow towards Namibia and join near the border to become the Okavango River (Mbaiwa, 2004). Most of the natural vegetation and of the river segments of this region remain in a pristine form, due to the low population density and the low influence of human activities, representing one of the regions of the earth that remain nearly untouched.

This study refers to the Angolan part of the basin which has a very particular topographic profile. The heads of the rivers are situated at an altitude of 1800 m (Cubango) and 1500 m (Cuito), while downstream they reach altitudes of 1000 m (Okavango).

In general the main feature of the landscape is the high number of wide valleys as rivers overflow the margins of this flattened region, converging southwards. The Kalahari sandy sediments occupy the larger zone of the basin, imposing a high level of geological background homogeneity in the whole area. The sandy sediments are mostly represented in the east part of the area, still, different sized sands can be noticed (Miguel, 2009). However, the northwest part of the basin, limited east by the Cuebe River, has fundamentally a rocky substrate constituted by 500 million-old, pre-cambric siliceous rocks and more embedded valleys, due to the particular topography and the substrate of this region. There is also a third substrate type which covers the border zone with Namibia. This region is composed essentially by alluvial material that, during the years, was deposited over the original sandy sediments (Miguel, 2009).

The climatic variation along the watershed has also its particularities. During the year, two general seasons can be documented, the rainy season from October to May with annual higher temperatures, and the dry season from June to September with lower temperatures. The driving factors that originate this variation are, on one hand, the altitude and, on the other, the wide extension of the area providing a climate gradient (Miguel, 2009). So, in a more specific way, two climatic zones can be defined: humid to sub-humid (Chitembo, Cuvango and Menongue) and semi-arid (Mucundi, Cuangar and Dirico). The differences between them are reflected by precipitation (101 mm/month and 51 mm/month) while the medium annual values of temperature remain 22ºC in both zones (Miguel, 2009).

The headwaters region of the Cubango sub-basin is covered by extensive areas of herbaceous species, colonizing small streams (Kgathi et al. 2006). Further east, the valleys of the Cubango River also include floodplain vegetation, most frequently composed of riverside forests and grasslands (Gomes, 2009). The valleys in the Cuito sub-basin on the other hand have a more homogenous vegetation mosaic. They are mostly dominated by floodplain vegetation, surrounded by large open fields seasonally flooded during the rainy season. As we move downstream, the *Brachystegia bakerana* forests dominate, and then progressively are substituted by dry land forest and finally dry savannas (Gomes, 2009). Because of the surface development and shallowness of the river corridors, the valleys tend to have extensive and diverse aquatic vegetation associations, with a patchy disposition, exploring the habitats of the multiple river channels (Kgathi et al., 2006).

Functional process zones

To obtain a river zoning describing process zones (*senso* Thorp et al., 2008) a network of sections was established on the Cubango river basin over the whole fluvial system (Figure 1). These sections had a mean length of 50 km, and were contiguous. The chosen network was judged fine enough to reflect the heterogeneity of the river system and long enough to favor data processing. The 154 sections were created throughout the entire basin using ArcGis 9.3.1. Sub-sections (3 km long) were marked at the center of each section and identified by a centroid to measure riverscape and riparian variables.

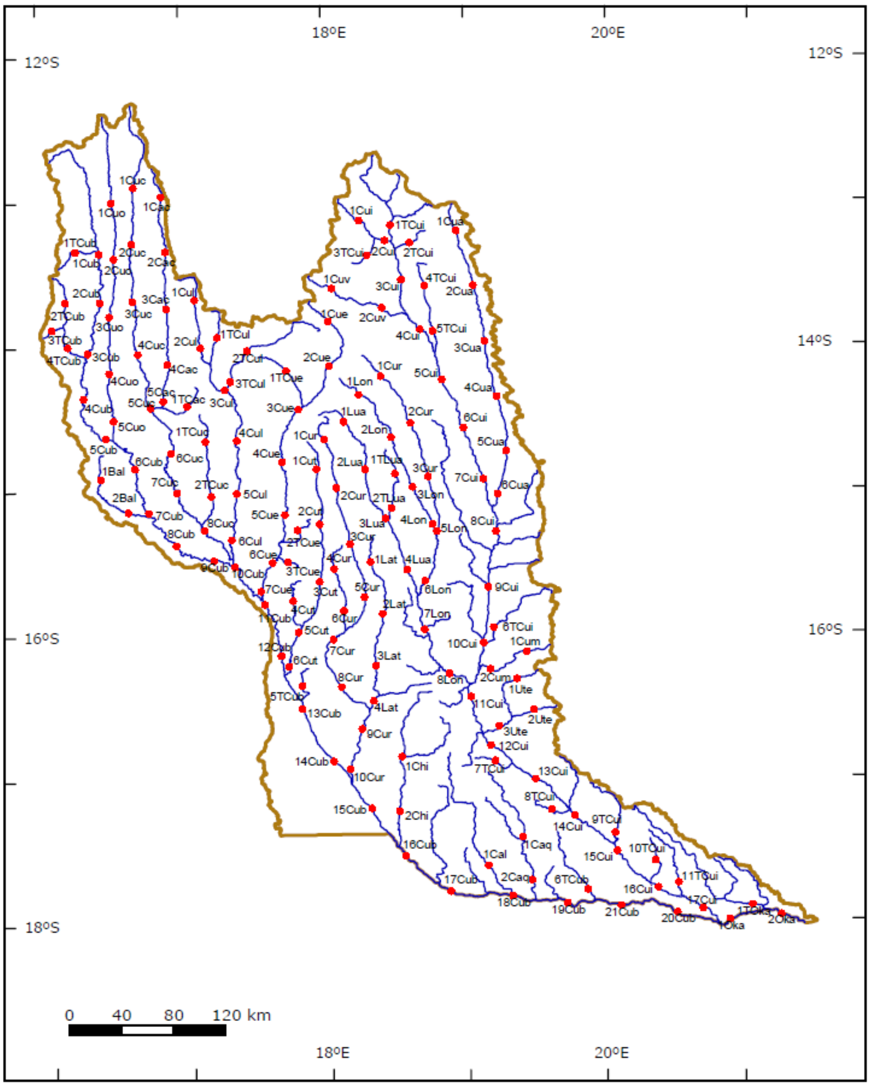


Figure 1 – Water sections and their respective centroid used for variables measurement base of the aquatic zoning of the river basin, including the different measurement points of the analyzed variables.

A hydrogeomorphological zoning was then obtained using climatic, environmental and geographic variables defined according to Thorp et al. (2008) to reflect entirely the riverine landscape hierarchy and to allow a good representation of the basins geomorphology. These variables where separated in two groups, the ‘reason’ variables (Table 1) and the ‘result’ variables (Table 2).

Table 1 – ‘Reason’ variables used for aquatic zoning of the river basin (Structural).

‘Reason’ Variables
Altitude (m)
Main Channel Width (m)
Mean Annual Precipitation (mm)
Strahler order factor
Average Annual Runoff (mm)
Flow (m3/s)
Drainage Basin (km2)
Distance to source (km)
Geology

The ´reason’ variables have or had a direct influence over the actual shape of the landscape of the river basin, they can also be called structural variables (hereafter the adopted denomination) and be described as an influence factor in the thousand year-long geographic evolution of the basin and on its climatic characteristics (Ward et al., 2002).

The altitude data, of each point was retrieved from the digital elevation data. This free-access data was produced by NASA and collected by the Shuttle Radar Topographic Mission (SRTM), in a project that included also the National Geospatial-Intelligence Agency, the German and Italian Space Agencies (http://dds.cr.usgs.gov/srtm/). The SRTM consisted in a specially adapted radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. Each digital elevation data is divided in a dense square grid and is used to calculate values relating the altimetry of a particular geographic spot. The resolution chosen for the digital elevation data, used for obtainment of the altitude values along the entire river basin, was the 90 m resolution and in general all the information can be extracted from a single image (Farr et al., 2007).

The drainage basin of each river section was obtained by hydrologic modeling. The procedure is centered on a deterministic algorithm named the ‘eight flow directions’ (D8) introduced by O'Callaghan & Mark (1984). Each cell of the grid square that compose the digital elevation data is linked to one of the eight neighboring cells, the algorithm uses the rule of greatest slope, assigning the direction of flow to the adjacent cell that has the greatest difference in ground altitude. The process was divided into two steps. The first one was to produce the drainage basins of the main rivers (Cubango and Cuito), the second one and after obtaining the key sections, each other remaining segment of the drainage network was calculated using the same method (Mónica Calçada, personal communication).

The technique of sequential water balance (Thornthwaite, 1948) was applied to the data from the hydrological stations in the area to obtain the average annual runoff values. Inputs to the model are mean monthly temperature, used to calculate the potential evapotranspiration, and monthly total precipitation. The water inflows and its outflows are calculated and transmitted in form of monthly values of the actual evapotranspiration, the water deficit, the water surplus and the soil-moisture storage (McCabe & Markstrom, 2007). The model calculates approximated values because it ignores the losses of precipitation, the profound infiltration from the system and the potential external contributions (Manuela Pires, personal communication). Annual runoff and flow values were converted from the previously acquired flow values.

The data obtained from the meteorology stations was used as central information for getting the Mean Annual Precipitation values of all 154 sections. An interpolation from the stations data was made to cover all the area of the river basin using weighted linear combinations of the available samples. According to Bohling (2005), the optimal interpolation is based on a regression against observed values of the basic linear regression estimator (z) of the surrounding data points. The different weights are assigned according to a data-driven weighting function. To determine the distance from each of the 154 designed sections to their particular rivers source, ArcGis 9.3.1. was used. The geologic characterization of each section was based on 1:1.000.000 geological map of Angola. Strahler stream order factor (Strahler, 1957) was also retained.

The 'result' variables represent the geomorphological consequence of the shape evolution of the basin and were driven by the force of the structural variables (Ward et al., 2002). These variables can also be called dynamic (the adopted denomination hereafter) and change their geomorphologic shape during the year and along the region of the river basin. Dynamic variables have values with a much higher variation during the year when compared with structural ones.

Dynamic variables were measured from ortophotomaps using the program Google Earth (Google Inc.). Using the 'Ruler' tool distances and lengths were measured and registered, excluding sinuosity. A three kilometer long sub-section was used at each mid-point. In each sub-section, three longitudinal equidistant transepts were chosen. Sinuosity (for further details see Figure 7.8 in Thorp et al., 2008) can be described as being the relation between channel length and valley length, and in most cases values vary between 1.0 for straight rivers and 3.0 for meandering rivers (Thorp et al., 2008). Thorp et al. (2008) defined meandering rivers as those with sinuosity greater than 1.3 and stated that its evolution depended on the slope, the texture and the meander behavior of the river. The main channel wavelength was measured along de axis of the channel considering its meander wavelength (note that its value depends on the channel width value).

Table 2 – 'Result' variables used for aquatic zoning of the river basin (Dynamic).

'Result' Variables
Valley Floor Width (m)
Channel Belt Maximal Mean Width (m)
Valley (Left and Right) Side Slope (%)
Down Valley (%)
Main Channel Wavelength (m)
Main Channel Sinuosity (1-3)
Channel Belt Sinuosity (1-3)
Width of isolated water accumulations
Width of isolated vegetation zones
∑ isolated water accumulations width (m)
∑ isolated vegetation zone width (m)

To obtain the hydrogeomorphic zoning (functional process zones, hereafter aquatic zones), the first step was to make a hierarchical cluster analysis using the values of the structural variables from the main rivers Cubango and Cuito (38 sections). To cluster the variables, squared Euclidean Distance between the variables and complete linkage method between groups were used (Electronic Statistics Textbook, 2013). A first validation was made using the structural variables and making a Discriminant Function Analysis (DA), to establish which variables distinguished each cluster group and assure that the zonation made sense. It is important to highlight that some of the remaining points (46) were ignored due to the lack of information of some of their variables. In second place and using the dynamic variables a DA was made again. The resulting linear equation was used to predict the affiliation of each remaining section (70) to its respective group (zone). At last a final DA was made using all the grouped sections (108) and only the dynamic variables. The classification matrix shown at the end of the DA process providing the prediction affiliation accuracy of the grouping was used to guarantee the successful zonation. A value greater than 80% was adopted as minimum so that the success of the prediction was considered good.

Fish Zonation

To obtain the fish distribution per section (presence/absence), all the available information was collected from various sources especially the IUCN Red List (www.iucnredlist.org) and the OKACOM Research Institute (www.orc.ub.bw). This information was complemented by technical reports from Angola and Namibia, and other bibliographic elements, notably field guides of the region (e.g. Skelton, 2001), and information from the colonial period available in Portuguese Museums.

Using presence/absence data, a similarity matrix was calculated with Primer-E 6 (PRIMER-E Ltd.), using the Bray-Curtis coefficient (Bray & Curtis, 1957) and complete linkage grouping (Clarke & Warwick, 2001). Afterwards and based on the similarity matrix a cluster was undertaken to group the different sections. This cluster only included the 38 sections of the two main rivers. To test the differences between groups (hereafter fish zones), a two-way Analysis of Similarity test (ANOSIM) was made (Clarke & Warwick, 2001).

Based on the same cluster results, a grouping of the species was made to find liaisons between particular species and fish zones. Furthermore, fish field data available at the Okavango River Basin Technical Diagnostic Analysis (2009) was also used to observe adherence of fish species to different fish zones. At last a SIMPER was made taking into account the created zones and it different fish species.

<u>**Connectivity Losses**</u>

To measure connectivity losses due to future dam construction on the fish communities a network analysis based on spatial graphs (Galpern et al., 2011; Eros et al., 2012; Segurado et al., 2013) was developed. As overall connectivity metric, the integral connectivity index (IIC), was selected to be quantified and compared to the initial conditions of nonexistent artificial barriers (Pascual-Hortal & Saura, 2006). In general, a graph network is represented by G = (N, L), where N represents a group of n nodes united by l links (L) (Erös et al., 2011). The river segments were defined as being habitat patches (nodes) and the confluences, as being the links between those patches. The dams were implemented at river segments and therefore corresponded to upstream node deletion and consequent habitat decrease. The future dams were considered as being total obstructions to up and downstream movements of the needing species and therefore dividing the original network into several constituents (Segurado et al., 2013).

Four major perturbation scenarios were considered, proposed in the basin planning and having different temporal horizons. The first scenario included all the dams that are projected to be constructed in a short future (10). The second included the first group of dams and a second group (7) that is projected to be constructed in a larger time horizon and only after the first phase of construction is finished. The third scenario included the two previous groups and another group of dams (10) that are considered as stand-by projects and are seen as having potential to reinforce the energy production. At last, the fourth scenario included all the previous dams and added the M'Pupa dam, close to the border with Namibia.

The scenarios were considered step by step. The difference between the original IIC, that reflected the present situation, and the altered IIC (dIIC), that reflected the situation after applying one of the four perturbation scenarios in a separate way, was used to understand the impact. The barriers were set all at the same time and the computed percentage of change in the IIC (dIIC) was outputted for each of the four scenarios considering the same starting point. By analyzing the different connectivity values the impact of the four scenarios on the actual connectivity of the rivers was weighted and compared.

Results

Geomorphic patterns

Five groups were obtained by clustering the 38 sections from the main rivers (Figure 2) therefore five different aquatic zones were designed along the rivers Cubango and Cuito, reflecting changes in climatic and geomorphologic characteristics from source towards downstream. The linear function was used to allocate the other river sections (70) to these five groups. The DA method was chosen due to its capacity to deal with categorical variables. The final validation was made with all 108 river sections obtaining a good percentage of allocation with the best discriminant variables (Table 3). Variables used for this analysis were the previously listed structural and dynamic variables.

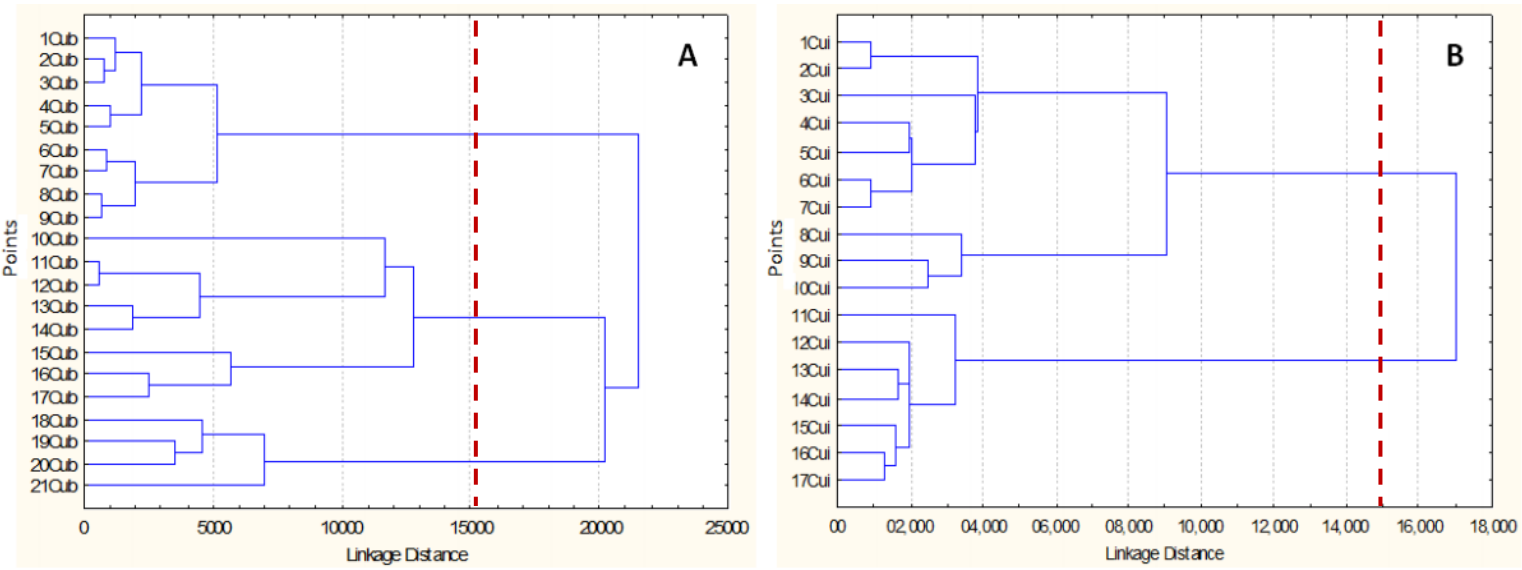


Figure 2 – Tree-clustering result of the two major rivers used to create the five different hydrogeomorphlogic zones (A – Cubango; B – Cuito).

Table 3 – Final Classification Matrix (DA) including all points and the dynamic variables.

Group	% Correct	G 1:1	G 2:2	G 3:3	G 4:4	G 5:5
G 1:1	87,50	21	3	0	0	0
G 2:2	92,86	1	13	0	0	0
G 3:3	66,67	0	1	6	0	2
G 4:4	87,10	0	0	0	27	4
G 5:5	86,67	1	2	0	1	26
Total	86,12	23	19	6	28	32

The environmental variability within the five aquatic zones showed a clear disparity between them (Table 4). For example, the lateral slope decreased as we move from North to South due to the decreasing influence of the mountainous areas, the increasing valley width and sandier bed sediments which converge to a plainer terrain. Another visible variation is the increasing main channel width downstream. In headwaters the channels are small and embedded, but as they head South they overflow the main channel and spread on the planform, becoming meandering and then latter with multiple channels and anastomosed. This pattern is clearly visible in the first three zones, which surround the Cubango River, but less obvious in the Cuito River, where the main channel dominates the planform and increases constantly, showing longer meander wavelength.

Of the five perceived zones, two represent the headwaters of the Cubango (zone 1) and Cuito (zone 4) Rivers, one the transition zone between the upstream and downstream areas of the Cubango River (zone 2) and the other two are associated to the regions downstream of both main rivers at the Namibian border (zone 3) and the confluence zone (zone 5). In general, the rivers present wide valleys, especially in the Cuito where the Kalahari sands predominate.

Upstream, the Cubango zone 1 stands out due to rockier and iron rich sediment, and its confined river channels. The limits of this zone are a mountainous region eastwards and the confluence with the Cuelel, and Cuchi Rivers southwards, whose inflow determines a change of zone. Zone 2 is characterized by a progressive enlargement of the main channel and the river valley, though the main channel is still relatively confined to its bed, becoming deeper (up to 4m in the beginning of the warm season) and wider (up to 50m, same season). Surrounding forest is savannah-like vegetation and this zone extends slightly above the convergence of the Chissimbo and the Cubango Rivers. Zone 3 has wider valleys and permanently flowing multiple river channels with large flooded plains interspersed with deeper and narrow channel areas.

Table 4 – Hydromorphological variability across the created aquatic zonation of the river basin (Mean with standard error).

Variable	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Main Channel Width (m)	25.80 ± 3.13	36.68 ± 9.10	125.93 ± 8.37	15.95 ± 2.45	90.35 ± 17.08
Valley Floor Width (m)	84.60 ± 8.71	79.24 ± 13.33	118.53 ± 11.95	72.39 ± 11.20	123.33 ± 20.36
Channel belt maximal mean width (3 km section)	254.71 ± 43.18	358.29 ± 74.30	1829.80 ± 618.79	1096.37 ± 155.77	1392.43 ± 466.78
Valley Side Slope (L)	1.76% ± 0.37	2.72% ± 0.57	1.23% ± 0.39	3.57% ± 0.71	1.44% ± 0.38
Valley Side Slope (R)	3.24% ± 0.37	3.79% ± 0.61	3.93% ± 1.41	3.20% ± 0.63	2.83% ± 1.27
Down valley slope (3 km section)	4.02% ± 0.52	3.14% ± 0.45	2.00% ± 0.71	2.03% ± 0.32	3.56% ± 1.11
Main channel wavelength (m)	401.95 ± 65.71	740.92 ± 243.51	1523.00 ± 353.19	214.38 ± 39.23	1029.44 ± 193.24
Channel belt sinuosity (1-3)	1.27 ± 0.02	1.21 ± 0.03	1.14 ± 0.02	1.22 ± 0.02	1.20 ± 0.02
Main channel sinuosity (1-3)	1.59 ± 0.04	1.55 ± 0.06	1.80 ± 0.04	1.61 ± 0.04	1.70 ± 0.09
Number of isolated water accumulations	1.52 ± 0.11	1.61 ± 0.36	1.67 ± 0.43	1.81 ± 0.25	1.19 ± 0.11
Sum of water accumulations width (m)	41.54 ± 4.25	57.14 ± 16.57	159.40 ± 31.21	56.41 ± 9.48	106.93 ± 20.98
Number of isolated vegetation zones	2.05 ± 0.18	2.59 ± 0.36	2.67 ± 0.43	2.76 ± 0.28	2.19 ± 0.11
Sum of vegetation zones width (m)	183.53 ± 41.87	298.33 ± 67.22	1671.07 ± 591.26	1037.23 ± 155.46	1284.17 ± 465.36

Zone 4 in the heads of the Cuito River, has a sandier sediment and less constrained river channels. The main channel flows through larger valleys when compared to the heads of the Cubango, with more complex corridors and a tendency to form inundated plains. As we move towards south, the river shows large sinuous meandering channels occupied by large quantities of emergent vegetation. The transition zone occurs on the confluence point between the Longa and the Cuito Rivers. Zone 5 is characterized by its large meandering channels and valley floors, with planform also meandering at a large spatial scale. The main channel develops into a braided, very complex and sprawling river including many side arms.

Zone 5 has unique characteristics after the confluence of the main rivers, Cubango and Cuito with large pristine floodplains and numerous meandering river arms, a very large valley and the absence of human populations.

Fish Communities

A total of 89 species were reported for the Angolan Cubango river basin (41 of them are potadromus species). The most representative genera are: *Aplocheilichthys* (4 species), *Barbus* (19 species), *Clarias* (6 species), *Sargochromis* (4 species), *Serranochromis* (6 species) and *Synodontis* (7 species), and the most abundant species: *Brycinus lateralis, Macrolestes acutidens* and *Opsaridium zambezense* (due to the captures made by the OKACOM). The fish zonation obtained from clustering fish assemblages per section, using presence/absence values (Figure 3) was practically coincident with the hydromorphological zonation, except for a few sections at the zone limits, e.g. two sections from zone 2 were attached to zone 3, on the confluence between the Cuatir and the Cubango Rivers. The ANOSIM two-way test also indicated significant differences therefore, the chosen partition points were assumed.

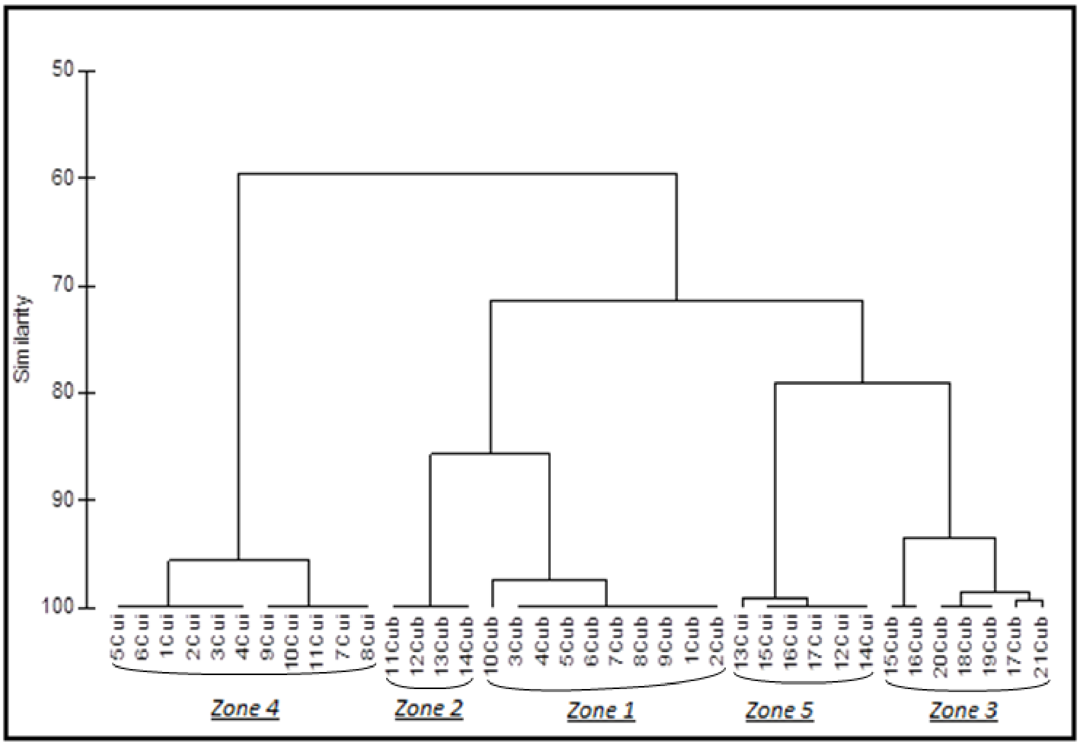


Figure 3 – Cluster Analysis made to obtain the five fish zones.

Zones 1 and 2, of the Cubango River are 85% similar and the distinctive species are *Barbus thamalakanensis*, *Chetia gracilis*, *Clarias dumerilii, Hippopotamyrus ansorgii* and *Hydrocynus vittatus* (Table 5). Zones 3 and 5 have 77% similarity and few distinctive species. Zone 4 is the most distinctive from all the others, having a similarity value of 60%. This reflects its unique sandy characteristics and that the species that inhabit it are almost exclusive there, e.g. *Barbus paludinosus*, *Brycinus lateralis, Clarias theodorae, Coptostomabarbus wittei, Marcusenius macrolepidotus, Micralestes acutidens Oreochromis andersonii* and *Oreochromis macrochir*. Overall, similarity between zones is high, indicating that many habitats can be used by most species, and that populations move freely in the riverscape to perform its life cycles. Table 5 shows the fish exclusive species of each zone.

Table 5 – Representative species of each designed fish zone based on the distribution areas provided by the IUCN and crossed over with the OKACOM made captures.

Zone	Species
1	*Aplocheilichthys macrurus; Chiloglanis fasciatus*
2	*Barbus radiatus; Labeobarbus codringtonii*
3	*Serranochromis macrocephalus; Synodontis woosnami*
4	*Hemichromis elongatus; Serranochromis robustus*
5	*Barbus breviceps; Synodontis macrostigma*

Connectivity losses

For the purposes of estimating connectivity losses, a total connectivity is assumed in the present situation. Table 6 expresses the expected impact on the river connectivity values considering the different dam building scenarios. Scenario one had the lowest dIIC value, representing the lowest connectivity decrease. The second scenario however had a similar value to the first one (the dIIC value was just slightly higher). The third scenario had a 59% connectivity reduction, having connectivity values of less than 50 % and a high dIIC, so the more damaging. Finally, the fourth scenario with dams built in aquatic zone 5, had the highest implications over the connectivity. The connectivity losses would affect the majority of the fish species present in the river basin. The longitudinal or lateral migrations would be directly and immediately affected by the obstruction of the river system.

Table 6 – Connectivity variation after applying the future dam construction scenarios to the actual riparian system.

	IIC	dIIC	% remaining connectivity	% connectivity reduction
Total	0.1004882	0	100%	0%
Scenario1	0.0519773	0.048511	51.7%	48.3%
Scenario2	0.0505381	0.049950	50.3%	49.7%
Scenario3	0.0411837	0.059305	41.0%	59.0%
Scenario4	0.0341378	0.066350	34.0%	66.0%

Discussion

Bethune et al. (2009) divided the Angolan site of the basin in seven homogenous Integrated Units of Analysis (for further details consult Okavango River Basin Environmental Flow Assessment Delineation Report nº: 04/2009, http://projects.inweh.unu.edu/inweh/display.php?ID=6263). However the authors added, to a regular biophysical division, a socio-economic variable that they used to define the boundaries of each biological zone. The biological zones that were identical after these divisions were then aggregated, so the resulting zonation is a mixture of physical, biological and human disturbance patterns, and did not include the morphologic characteristics of the riparian system. Nonetheless, excluding the IUA 3, which refers only to the Cuebe River due to its water quality problems and human aggregation, all the other zones fit into some of the five aquatic zones designed in this study. Therefore a basic zoning structure of physical characteristics could be established and demonstrated, that will influence the river channel and its biotic components, therefore can be used to deal with human impacts and for ecological management purposes.

Furthermore, the OKACOM report (Bethune et al., 2009) did not include the geomorphologic characteristics of the riparian system and the floodplain, which are important for habitat structure, especially under large seasonal changes in water level. A study developed by Cianfrani et al. (2009) showed the importance of a longitudinal heterogenic channel and stated that its consequent mixed morphology characteristics support high fish community richness and abundance. It is known that habitat heterogeneity has a very strong influence on species richness (Huston, 1994) and that heterogeneity is a consequence of the channels' different morphological characteristics.

Because of habitat resources exploitation by different fish communities, throughout their life cycles, the five fish zones have a very high level of coincidence with the designed aquatic zones and their morphologic attributes. The driving variable of our fish zoning was the distribution areas of the different species. As viewed before, the distribution areas or habitats depend in many different ways from the river channel structure. The created fish zones reflect the prevailing habitat of the existent fish communities. It also showed that complex interactions are present, over space and time, and that few species are limited only to one zone, but rather use two or more aquatic zones.

But even so, is there any ecological significance when crossing these both set of zones over? The five distinct aquatic zones are clearly different from each other from a geomorphologic, climatic and environmental point of view. This is also a result of the presence of the Kalahari sandy sediment in all zones, with the exception of the Cubango heads, which allows the water to excavate, intricate and interconnected pathways in the river bed while increasing the channel. While flow increased downstream in both rivers, runoff decreases, presumably because of the higher infiltration, especially after the Cuito confluence. Food and reproduction habits and resource partitioning depend at a great level from the river channel geomorphologic forms, water hydraulics and riparian vegetation patches. Each single zone has its own different hydro-morphological structure and characteristics, consequently leading to the formation of different habitats and afterwards to different biological communities, which are reflected in the clustered distribution areas for the different fish species and fish communities.

Lamouroux et al. (1999) defined that geographic regions act directly on the species abundance and that hydraulic drivers appeared to be a main determinant of fish community configuration. They also issued that hydraulics affect fish communities within a given geographical context in a large scale. It is understandable that these two factors are the driving motors of fish communities' evolution and their distribution. The climate-dependent flow variations also tend to alter and to influence the communities structure (Propst & Gido, 2004) and to trigger reproductive migrations and spawning by flooding partially the surrounding plains.

According to Darwall et al. (2008) this freshwater region (south region of the African continent) is considered to contain extraordinarily high numbers of species and is one of the few eco-regions that remains unobstructed (Liermann et al., 2012).The importance of maintaining such a rich and diverse fish community is high. Dudgeon et al. (2006) described that freshwater biodiversity as being 'a broad variety of valuable goods and services for human societies' and some of those goods are unique. The existence of healthy fish communities is essential for the ecological stability of the river system and its future development (Power, 1992). It is vital to value the freshwater biodiversity and its importance to society must be reported successfully to all (Dudgeon et al., 2006), so its significance is clear and its welfare is guaranteed throughout the years. The value of freshwater biodiversity can be pictured by three main facts: its strong role in economic productivity and to people's livelihoods, its high importance as a well, and consequently, a source of genetic information and its vital significance in providing essential ecosystem services (Costanza et al., 1997; Covich et al., 2004; Darwall et al., 2008).

Connectivity decreases resulting from dam construction and other barriers to movement, can have several consequences on the fish communities' richness and its various habitats (Vörösmarty et al., 2010). According to the connectivity dimensions (Ward, 1989), the longitudinal dimension (along the channel) is regarded as being the most important for fish, due to its capacity to insure up- and downstream migrations for reproduction, feeding and habitat colonization reasons (Lucas & Baras, 2001). The obstruction of migration routes is only one of the several impacts that dams can have on the river system. Dams modify and fragment habitats, reduce resource transport across the rivers and can lead to potential genetic impoverishment (Branco et al., 2011; Hall et al., 2011).

In the past years, the connectivity loss in African rivers has been a trendy topic of discussion, due to its increasing importance (Mantel et al., 2010 and Richter et al., 2010). Dam construction and its impacts on South African rivers are well documented by several authors and organizations (e.g. http://www.southafricandams.co.za/). Mantel et al. (2010) suggest the importance that small dam construction can have and its cumulative impacts on the entire riparian system and its water quality. The loss of the natural flow regime and loss of essential habitat characteristics is one of the biggest problems for the affected fish species (Bunn & Arthington, 2002). An important example for this essential characteristics loss is the Kafue River in Zambia where, since the absence of proper environmental flow releases, the vegetation, fisheries and food production systems have been harshly affected (Richter et al., 2010). Other several examples of environmental impacts resulting from dam construction on the riparian systems in the African continent exist such as the regulation of the Pongolo River in South Africa and of the Volta River in Ghana (Pottinger, 1996). The loss of connectivity that has been observed in different African rivers and the consequences for the systems balance cannot be ignored (Bunn & Arthington, 2002).

Due to its present nearly pristine conditions, the Okavango river basin needs to be preserved as far as possible from dam construction. The impacts of river barriers can be evaluated by the alteration of the IIC value, after the implementation of the first and most mild scenario. The fact that almost 50% of the longitudinal connectivity is lost shows the severe consequences that dam construction would have for the present species, for their habitats and life cycles.

A connectivity loss of 50%, if not mitigated by adequate fish passes and minimal flow requirements, will have severe consequences for the potadromous species present in the river basin and would lead to isolation, fragmentation and declination of their populations (Lasne et al., 2007; Branco et al., 2011), notably in hidromorphologic zone 1, where most phase 1 dams will be built. The second scenario would aggravate the situation and the reduction value of the third and fourth scenarios would mean a total breakdown of the connectivity and therefore of the fish communities' richness. The remaining connectivity after the construction of the projected dams would be shorten to 30% and would mean a total fragmentation of the existing habitats, and affect the aquatic species moving between feeding and spawning grounds (Hall et al., 2011; Liermann et al., 2012). In case of the Cubango-Okavango river basin, twenty-two of the twenty-eight dams are planned to be constructed in the first aquatic region. The impacts would affect not only the migrating species that have bigger habitat exigencies, but also the resident species that would lose their essential habitats (Branco et al., 2011). One consequence for the resident species would be submersion of the lotic environment and its transformation into a lentic environment, therefore leading to an absence of spawning/feeding grounds and a consequent decline of the populations (Larinier, 2000; Wu et al., 2004) and the spawning areas (Larinier, 2000; Lucas & Baras, 2001).

Segurado et al. (2013) stated the innovative potential of the graph method applied to the prediction of the impacts caused by the construction of dams. According to the authors the biggest advantage is that the reported method is 'based on variations in IIC and that it relies on single measures that are quantified in relation to the original (reference) conditions of nonexistent artificial barriers'. Bunn et al. (2000) also reported the increasing importance of this method in an ecological framework and that it 'represents a promising step forward in that regard'.

The same author also states that these approaches can have a big influence on ecological processes linked to connectivity. This big label to connectivity is also shown in its capacity to incorporate habitat aptness of a single species or a group of species into its overall availability (Pascual-Hortal & Saura, 2006). At last and not like other connectivity indices, this method has the important capacity of evaluating, from an individual or grouped point of view, the weight of landscape elements, to the maintenance of the correct riparian connectivity (Saura & Torne, 2009; Saura & Rubio, 2010).

The designed fish zones show that the species richness is high and that many species can be found in more than one region. The biological interdependence between zones is large and the obstruction of the fundamental channels would affect the future aquatic diversity of the Cubango-Okavango river basin. In the third scenario of construction plans, the M'Bambi dam is the key cause for the interruption in the Cubango River. Its southern position would affect a big set of species present in the south zone of the Cubango River and in the Okavango River that would be willing to migrate upstream.

According to Scott (2012), the annual occurring floods are the main driver and the most important ecological process of the fish communities in this river basin. This author also refers the fact that the fish distribution throughout the entire system is in general regulated by the annual flood cycle. Dudgeon et al. (2006) draw attention to water regimes and its high influence over the aquatic biodiversity. They also refer that the preservation of natural variability in flows and water levels is vital to maintain freshwater biodiversity and the habitats of the different communities.

The different species that occur in the Cubango-Okavango river basin present a very distinguished number of trophic, reproductive, habitation and migratory guilds making clear that this riparian system has numerous and rich characteristics that are essential for these species. Fish guilds are deeply connected to the characteristics of the system and its annual variations. Each species that inhabits the river basin has its own uniqueness, to be preserved, and careful mitigation of future dam building should be planned in order to insure a sustainable development in water resources allocation.

The importance of fish passages for the different migrations is known and well documented (e.g. Coutant & Whitney, 2000; Larinier, 2000 and Schilt, 2007). The existing conflict between the human needs and the species needs is real, the fish passages minimizes this friction, understanding how to design and control these structures to do the least harm possible to the ecosystems that we modify is essential for their maintenance (Schilt, 2007).

Dam construction and the need of this fish passes has also reached South Africa and became, in the past years, a major need (Larinier, 2000). It is true that their effectiveness depends on various factors, on the conditions of the site and the passes themselves and that innovation is needed, but their mitigation benefits are indispensable (Schilt, 2007). However none are yet projected to be constructed in future in this region.

References

Amoros, C. & Bornette, G., 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology, 47, pp. 761–776.

Bethune, S.; Mazvimavi, D. and Quintino, M., 2009. Delineation Report. Report 04-2009 EPSMO/BIOKAVANGO Okavango Basin Environmental Flows Assessment Project, OKACOM, Maun, Botswana. 67 pp.

Bohling, G., 2005. Kriging. Kansas Geological Survey.

In: http://people.ku.edu/~gbohling/cpe940/Kriging.pdf.

Branco, P.; Segurado, P.; Santos, J.M.; Pinheiro, P. and Ferreira, M.T., 2011. Does longitudinal connectivity loss affect the distribution of freshwater fish?. Ecological Engineering, 48, pp. 70–78.

Bray, J.R. and Curtis, J.T., 1957. An ordination of the upland forest communities of southern Wisconsin. Ecological Monographs, 27, pp. 325–349.

Bunn, A. G.; Urban, D. L. and Keitt, T. H., 2000. Landscape connectivity: a conservation application of graph theory. Journal of Environmental Management, 59(4), pp. 265-278.

Bunn, S. E. and Arthington, A. H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental management, 30(4), pp. 492-507.

Cianfrani, C. M.; Sullivan, S. M. P.; Hession, W. C. and Watzin, M. C., 2009. Mixed stream channel morphologies: implications for fish community diversity. Aquatic Conservation: Marine and Freshwater Ecosystems, 19(2), pp. 147-156.

Clarke, K.R. and Warwick, R.M., 2001. A further biodiversity index applicable to species lists: variation in taxonomic distinctness. Marine Ecology Progress Series, 216, pp. 265–278.

Costanza, R.; d'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O’Neill, R.V.; Paruelo, J.; Raskin, R.G.; Sutton, P. and Van den Belt, M. ,1997. The value of the world's ecosystem services and natural capital. Nature, 87(6630), pp. 253-260.

Coutant, C. C. and Whitney, R. R., 2000. Fish behavior in relation to passage through hydropower turbines: a review. Transactions of the American Fisheries Society, 129(2), pp. 351-380.

Covich, A. P.; Austen, M. C.; Bärlocher, F.; Chauvet, E.; Cardinale, B. J.; Biles, C. L.; Inchausti, P.; Dangles, O.; Solan, M.; Gessner, M.O.; Statzner, B.and Moss, B., 2004. The role of biodiversity in the functioning of freshwater and marine benthic ecosystems. BioScience, 54(8), pp. 767-775.

Darwall, W.; Smith, K.; Allen, D.; Seddon, M.; Mc Gregor Reid, G.; Clausnitzer, V. and Kalkman, V., 2008. Freshwater biodiversity – a hidden resource under threat. In: J.-C. Vié, C. Hilton-Taylor and S.N. Stuart (eds.) The 2008 Review of The IUCN Red List of Threatened Species. IUCN, Gland, Switzerland

Dudgeon, D.; Arthington, A.; Gessner, M.; Kawabata Z.; Knowler, D.; Lévêque, C.; Naiman, R.; Prieur-Richard, A.; Soto, D.; Stiassny, M. and Sullivan, C., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews, 81, pp. 163–182.

Erös T, Schmera D, Schick RS (2011) Network thinking in riverscape conservation—a graph-based approach. Biol Conserv 144:184–192

Erös, T.; Olden, J.D.; Schick, R.S.; Schmera, D. and Fortin, M-J., 2012. Characterizing connectivity relationships in freshwaters using patch-based graphs. Landscape Ecology, 27, pp. 303–317.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S.; Kobrick, M.; Paller, M.; Rodriguez, E.; Roth, L.; Seal, D.; Shaffer, S.; Shimada, J.; Umland, J.; Werner, M.; Oskin, M.; Burbank, D. and Alsdorf, D., 2007. The shuttle radar topography mission. Reviews of geophysics, 45(2).

Galpern, P.; Manseau, M. and Fall, A., 2011. Patch-based graphs of landscape connectivity: a guide to construction, analysis and application for conservation. Biological Conservation, 144, pp. 44–55.

Gomes, A., 2009. Análise Diagnóstica Transfronteiriça da Bacia do Rio Okavango: Módulo do Caudal Ambiental, Relatório do Especialista, País: Angola, Disciplina: Vegetação, OKACOM, Maun, Botswana.

Hall, C.; Jordaan, A. and Frisk, M., 2011. The historic influence of dams on diadromous fish habitat with a focus on river herring and hydrologic longitudinal connectivity. Landscape Ecology, 26, pp. 95–107.

Huston, M. A., 1994. Biological diversity: the coexistence of species on changing landscapes. Cambridge Univ. Press, Cambridge.

Jackson, D.; Peres-Neto, P. and Olden, J., 2001. What controls who is where in freshwater fish communities — the roles of biotic, abiotic, and spatial factors. Canadian Journal of Fisheries and Aquatic Sciences, 58, pp. 157–170.

Kgathi, D. L.; Kniveton, D.; Ringrose, S.; Turton, A. R.; Vanderpost, C. H. M.; Lundqvist, J.; and Seely, M., 2006. The Okavango; a river supporting its people, environment and economic development. Journal of Hydrology, 331(1), pp. 3-17.

Lamouroux, N.; Olivier, J. M.; Persat, H.; PouilLy, M.; Souchon, Y. and Statzner, B., 1999. Predicting community characteristics from habitat conditions: fluvial fish and hydraulics. Freshwater Biology, 42(2), pp. 275-299.

Lamouroux, N.; Olivier, J.; Capra, H.; Zylberblat, M.; Chandesris, A. and Roger, P., 2006. Fish community changes after minimum flow increase: testing quantitative predictions in the Rhône River at Pierre-Bénite, France. Freshwater Biology, 51, pp. 1730–1743.

Larinier, M., 2000. Dams and Fish Migration, World Commission on Dams - Environmental Issues, Dams and Fish Migration.

Lasne, E.; Lek, S. and Lafaille, P., 2007. Patterns in fish assemblage in the Loire floodplain: the role of hydrological connectivity and implications for conservation. Biological Conservervation, 139, pp. 258–268.

Liermann, R., 2007. Ecohydrologic impacts of dams: A global assessment. PhD Dissertation, Umeå University.

Liermann, R.; Nilsson C., Robertson, J. and R. Ng., 2012. Implications of dam obstruction for global freshwater fish diversity. BioScience, 62, pp. 539-548.

Lucas, E. and Baras, M., 2001. Migration of Freshwater Fishes. Blackwell Science

Malard, F.; Tockner, K. and Ward, J.V., 1999. Shifting Dominance of Subcatchment Water Sources and Flow Paths in a Glacial Floodplain, Val Roseg, Switzerland. Arctic, Antarctic, and Alpine Research, 31(2), pp. 135-150.

Mantel, S. K.; Muller, N. W. and Hughes, D. A., 2010. Ecological impacts of small dams on South African rivers Part 2: biotic response-abundance and composition of macroinvertebrate communities. Water SA, 36(3), pp. 361-370.

Mbaiwa, J.,2004. Causes and possible solutions to water resource conflicts in the Okavango River Basin: The case of Angola, Namibia and Botswana. Physics and Chemistry of the Earth, 29, pp. 1319–1326.

McCabe, G. and Markstrom, S., 2007. A monthly water-balance model driven by a graphical user interface. U.S. Geological Survey Open-File report 2007- 1088, 6 pp.

Mendlesohn, J. and el Obeid, S., 2004. Okavango River - The Flow of a Lifeline, Struik.

Miguel, G., 2009, Análise Técnica, Biofísica E Sócio-Económica do Lado Angolano Da Bacia Hidrográfica do Rio Cubango: Subsídio Para o Conhecimento Hidrogeológico, Relatório de Hidrogeologia, OKACOM, Maun, Botswana.

Morais, M., 2009. Análise Diagnóstica Transfronteiriça da Bacia do Rio Cubango (Okavango): Módulo da Avaliação do Caudal Ambiental, Relatório do Especialista, País: Angola, Disciplina: Ictiofauna, OKACOM, Maun, Botswana.

Moulton, T. & Souza, M., 2006. Conservação com base em bacias hidrográficas. Biologia da Conservação, pp. 45-52. Ed. Universidade do Estado do Rio de Janeiro.

Nilsson, C. and Berggren, K., 2000. Alterations of Riparian Ecosystems Caused by River Regulation. BioScience, 50(9), pp. 783-792.

O'Callaghan, J. F. and Mark, D. M., 1984. The extraction of drainage networks from digital elevation data. Computer vision, graphics, and image processing, 28(3), pp. 323-344.

Pascual-Hortal, L. and Saura, S., 2006. Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation. Landscape Ecology, 21(7), pp. 959-967.

Petts, G. E. and Amoros, C., 1996. Fluvial hydrosystems. Springer

Pottinger, L., 1996. Environmental Impacts of Large Dams: African examples.

In: http://www.internationalrivers.org/resources/environmental-impacts-of-large-dams-african-examples-202.

Power, M. E., 1992. Habitat Heterogeneity and The Functional Signifiance of Fish in River Food Webs. Ecology, pp. 1675-1688.

Propst, D. L. and Gido, K. B., 2004. Responses of native and nonnative fishes to natural flow regime mimicry in the San Juan River. Transactions of the American Fisheries Society, 133(4), pp. 922-931.

Richter, B.D.; Postel, S.; Revenga, C.; Scudder, T.; Lehner, B.; Churchill, A. and Chow, M., 2010. Lost in Developments shadow: the downstream human consequences of dams. Water alternatives, 3(2), pp. 14-42.

Saura, S. and Rubio, L., 2010. A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape. Ecography, 33(3), pp. 523-537.

Saura, S. and Torne, J., 2009. Conefor Sensinode 2.2: a software package for quantifying the importance of habitat patches for landscape connectivity. Environmental Modelling & Software, 24(1), pp. 135–139.

Schilt, C. R., 2007. Developing fish passage and protection at hydropower dams. Applied Animal Behaviour Science, 104(3), pp. 295-325.

Schumm, S., 1981. Evolution and response of the fluvial system, sedimentologic implications. Defense Technical Information Center.

Scott, L., 2012. Freshwater Ecoregions of the World – Okavango.

In: http://www.feow.org/ecoregions/details/okavango

Segurado, P.; Branco, P. and Ferreira, M. T., 2013. Prioritizing restoration of structural connectivity in rivers: a graph based approach. Landscape Ecology, pp. 1-8.

Skelton, P.H., 2001. A Complete Guide to the Freshwater Fishes of Southern Africa. Southern Book Publishers, Halfway House.

StatSoft, Inc., 2013. Electronic Statistics Textbook. Tulsa, OK: StatSoft - http://www.statsoft.com/textbook/.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Trans Am Geophys Union, 38, pp.913–920.

Strayer, D. and Dudgeon, D., 2010. Freshwater biodiversity conservation: recent progress and future challenges. Journal of the North American Benthological Society, 29(1), pp. 344-358.

Thorne, C. R.; Hey, R. D. and Newson, M. D., 1997. Applied fluvial geomorphology for river engineering and management. John Wiley & Sons Ltd.

Thornthwaite, C. W., 1948. An approach toward a rational classification of climate. Geographical review, 38(1), pp. 55-94.

Thorp, J. H., Thoms, M. C., and Delong, M. D., 2008. The riverine ecosystem synthesis: toward conceptual cohesiveness in river science. Elsevier.

Vörösmarty, C. J.; McIntyre, P. B.; Gessner, M. O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Liermann, C.R. and Davies, P. M., 2010. Global threats to human water security and river biodiversity. Nature, 467(7315), pp. 555-561.

Ward, J. V., 1989. The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society, pp. 2-8.

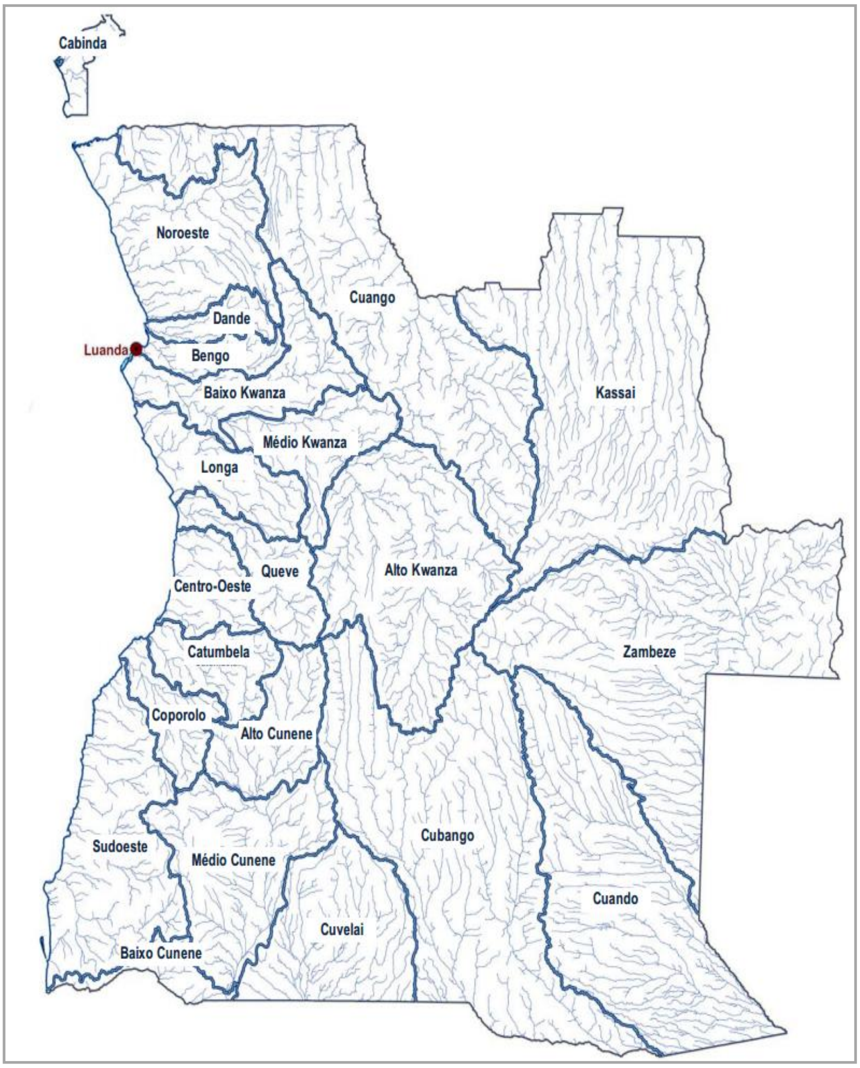
Ward, J. V. & Tockner, K., 2001. Biodiversity: towards a unifying theme for river ecology. Freshwater Biology, 46, pp. 807-819.

Ward, J. V.; Tockner, K.; Arscott, D. B. and Claret, C., 2002. Riverine landscape diversity. Freshwater Biology, 47(4), pp. 517-539.

Willis, S.; Winemiller, K. and Lopez-Fernandez, H., 2004. Habitat structural complexity and morphological diversity of fish assemblages in a Neotropical floodplain river. Oecologia , 142, pp. 284–295.

Wu, J.; Huang, J.; Han, X.; Gao, X.; He, F.; Jiang, M.; Jiang, Z.; Primack, R.B. and Shen, Z., 2004. The three gorges dam: an ecological perspective. Frontiers in Ecology and the Environment, 2(5), pp. 241-248.

Attachments



The Angolan river basins.

Study area:

Cubango–Okavango river basin (southeast, frontier with Namibia)

(Page 8)

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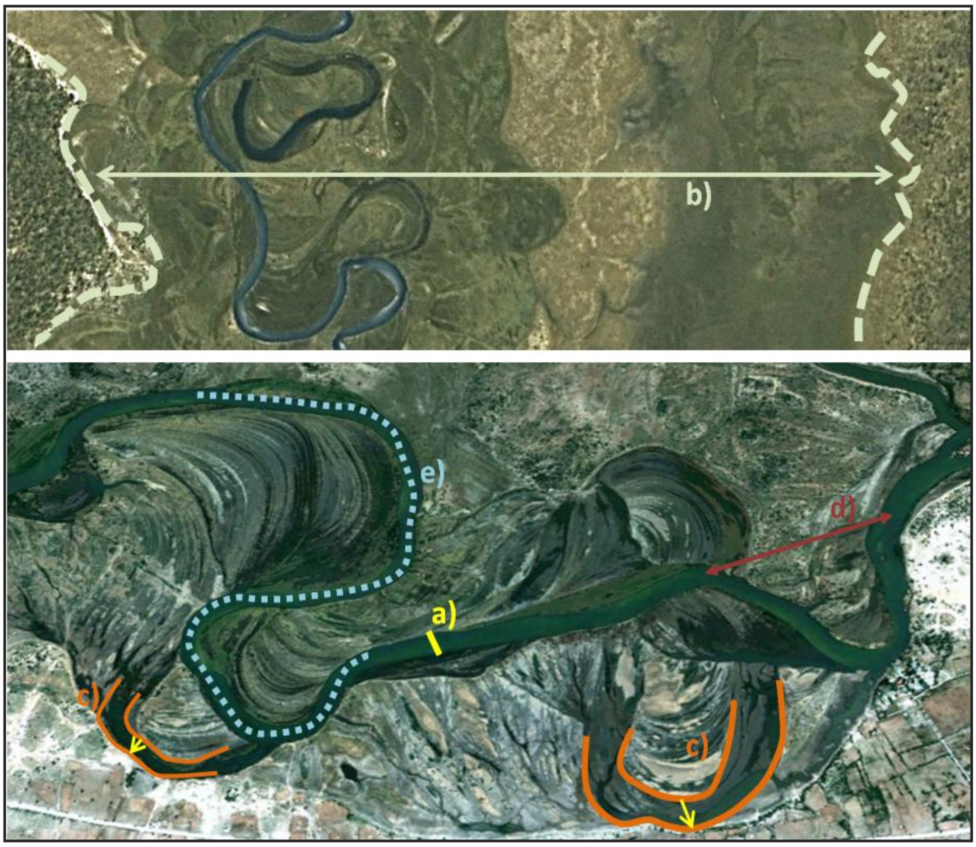


Dynamic variables (examples):

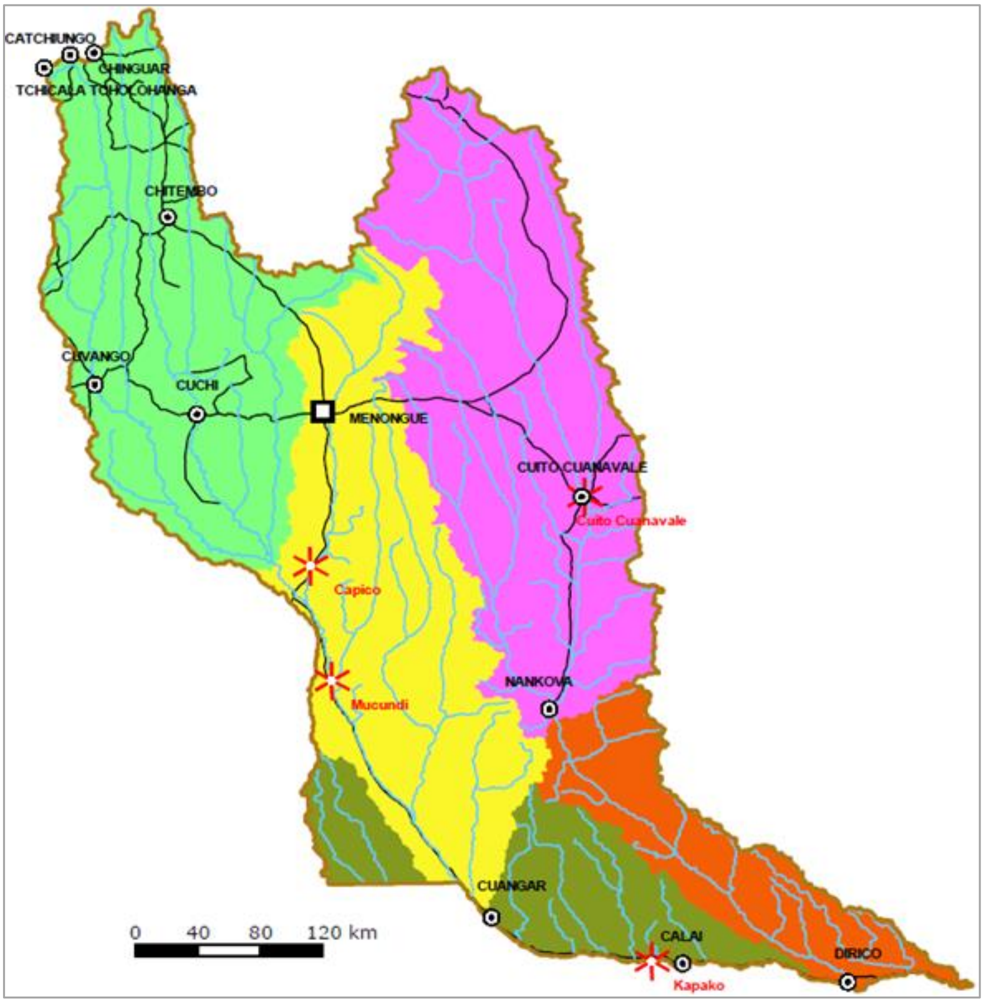
b) Valley Floor Width

c) Width of isolated water accumulations

d) Main Channel Wavelength

e) Main Channel Sinuosity

(Page 13)



Five hydro-geomorphologic zones and the most important cities in the river basin.

(Pages 16 and 17)